BELLCOMM, INC.

SUBJECT: Saturn V EDS Effectiveness Study
Case 330

DATE: March 22, 1967

FROM: T. F. Loeffler

ABSTRACT

A summary of recent activities and the present status of the Saturn V Emergency Detection System Effectiveness Study is presented.

The Boeing Flight Dynamics (computer) simulation program BHA-0030, which is the primary analytical tool in working this problem under task MSFC-152, is briefly described.

The latest simulation runs by their program indicate that changes in the Flight Control System and structural strengthening of several critical launch vehicle joints will be required. MSFC is proceeding to make the changes.

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(NASA-CR-153829) SATURN 5 EDS EFFECTIVENESS STUDY (Bellcomm, Inc.) 28 p

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MEMORANDUM FOR FILE

This memorandum summarizes recent activity and the present status of the Saturn V Emergency Detection System (EDS) Effectiveness Study being conducted by The Boeing Company (TBC) for MSFC. References 1 through 5 show the evolution of the problem and therefore only a short recapitulation is given in this memorandum.

On November 9, 1966, TBC reported the results of computer simulations of the effects of 11 propulsion/control malfunctions upon the launch vehicle structure (Reference 1). These results indicated that little or no warning time is available to save the spacecraft and the crew when these malfunctions occur near maximum $Q\alpha$. The purpose of the analysis was to determine whether the vehicle breaks up when a given malfunction occurs in a given manner, at particular flight times, and under given wind conditions. If the vehicle failed, then measurable EDS parameters (e.g., q-ball output, or attitude rates) were examined to determine what limit value could be used as a useful abort cue. The results indicated that for 8 of the 11 malfunctions there would be less than one second warning time from malfunction to vehicle breakup in which to manually abort if the EDS limits were set outside the three sigma envelope of normal excursions in attitude rate and q-ball delta-pressure. Results for other malfunctions were found to be comparably bad from a crew safety standpoint.

Subsequent TBC work, using the structural load time history, (see References 3 and 4) indicated slightly later breakup time(s) than those calculated from the limits of vehicle angle of attack, α, and effective engine gimbal angle, β. This provided more warning time than the first results but still not enough for detection and initiation of a safe abort (see Reference 3).

During the seventh Flight Limits Subpanel Meeting of February 14, 1967, (see Reference 5) MSFC and TBC gave a status report of the work done under task MSFC-152. The technical approach and intermediate results of the study are described in Appendix A. The scope of the study was to define acceptable EDS effectiveness for the vehicle during S-IC burn. MSC was requested to furnish the spacecraft structural capability and to critically reexamine the

LEV limits. Consideration was being given to adding sensors on the S-IC control-engine actuators to indicate "hardover condition." The proposed logic would use the present engine status lights to show engine actuator hardover as well as an engine-out situation. The EDS subpanel of the Crew Safety Panel was to determine the feasibility of adding these actuator sensors.

The R-P&VE Structures Division of MSFC presented results of their preliminary structural analyses and recommendations for definition of required structural strengthening of the launch vehicle on February 27, 1967. This presentation was covered in Reference 4.

Mr. C. Hagood, MSFC, arranged a February 23, 1967, briefing for the author on the Boeing (computer) program, its equations, input parameters, assumptions, etc. Messrs. J. Gelzer and D. Chichester of TBC described the overall problem, the general method of attack, and the BHA-0030 computer program.

The BHA-0030 simulation program is a very large (over 10,000 instructions) and complex FORTRAN "H" program. It has a three-link overlay structure because the memory capacity of the IBM 7094 is not sufficient to enable single-pass processing. It uses the "Runge-Kutta-Gill" integration method and "Z-transform" derived control filters. It has a Benson-Lehner output plotter. The simulation runs at 30 times real time. Boeing is converting to an IBM 360-65 computer which can perform the simulation in 20 times real time.

No program flow charts have been prepared or planned. A listing of the various sets of equations, which are operated upon by the 22 sections of the program, are available from the author of Reference 4. The most significant simulation features of the program include:

1. Six-degree-of-freedom, rigid body dynamics (first stage flight).

2. Eight flexible-body bending modes (four in pitch plane, four in yaw plane, no cross-coupling).

3. Twelve sloshing degrees of freedom (in plane only) (pitch and yaw for the six main propellant tanks).

4. Ideal first order lag engine actuator model.

5. Second order representation of engine itself.

6. Third order representation of thrust vector model*

7. Control system model includes motion sensors, gain switching, and filter characteristics.

8. A 51 point distributed-mass model of the vehicle.

9. An extensive 19 panel distributed model of the vehicle with non-linear aerodynamics.

10. Capacity for introduction of any predetermined malfunction.

11. A "scatter" capability within a 3σ range of selected parameters.

12. The Standard Apollo Coordinate System.

13. International scientific (metric) units (optional English system output also available).

14. Bending moments, forces, etc. at 18 vehicle sections between the 19 aerodynamic panels.

The 22 sections of the program provide input or solve equations as follows:

A. Vehicle Dynamics:

1. Vehicle mass at each of 51 points reflecting fuel and oxidizer flow rates of the appropriate engine.

2. Earth's gravity takes into account earth-oblateness and a non-spherical gravity model.

3. Translational equations of motion.

4. Rotational equations of motion.

5. Slosh equations of motion in pitch and yaw planes for each of six propellant tanks.

6. Vibrational equations of motion.

7. Inertial and relative velocity equations.

8. Vehicle position.

---

*This model takes into account pressure and acceleration effects upon both the thrust and the fuel/LOX flow.

9. Coordinate transformations.

10. Inertial attitude.

11. Aerodynamic effects on 19 vehicle panels.

12. Resultant moments at 18 vehicle stations.

13. Resultant forces at 24 vehicle stations.

B. Vehicle Systems:

14. Launch Vehicle Digital Computer (LVDC) response and effects.

15. Control Computer response and effects.

16. Thrust Vector Control System response and effects.

17. Propulsion system equations.

C. Parametric Values:

18. Scatter equations (to account for manufacturing tolerances, minor changes in estimated values, etc.)

19. Attitude and rate limits.

20. Initialization of all variables.

D. Structural Load Calculations:

21. Composite Bending Moments.

22. Resultant structural loads.

As apparent from the above, the vehicle structural and aerodynamic models are of an elastic body, distributed type. The mass of the vehicle, concentrated at 51 "lumped-mass" points, is calculated as a function of fuel/LOX flow, sloshing, etc. The individual masses are concentrated along the centerline of the vehicle. The vehicle is divided into 19 panels (see Figure 1) with the junctions corresponding to critical vehicle structural joints. The vehicle equations of motion are used to calculate the angle of attack and the Mach number at these aerodynamic reference panels. Using these quantities as the independent variables, the three-dimensional tables (see Figure 2) are entered, and the coefficients of aerodynamic force and moment, C_{ni} and C_{mi} respectively, at each reference panel are obtained.

The aerodynamic forces and moments are then determined by use of the values of local dynamic pressure q_i, and the coefficients, C_{ni} and C_{mi}, for the reference panels. These values are summed to check against total vehicle aerodynamics (see Figure 3). It should be noted that moments are determined at 18 stations (panel junctions), while (axial) forces are calculated at 24 stations. This is done because at certain ("Y" ring) joints the axial loads are discontinuous and hence, the forces must be determined on both sides of these interfaces. The pitch and yaw plane components of these forces/moments are then used as forcing functions in the translational, rotational, and vibrational equations of motion, as well as the total vehicle bending moment calculations.

This aerodynamic model considers the effects of a wide range of non-linearities of Mach number, angle of attack, dynamic pressure, and aerodynamic damping. Winds are simulated in both direction and magnitude; hence, gust effects can be included. Engine failures are simulated by using 3σ worst case values obtained from experimental engine shut-down data; approximate decay time from 90% to 10% of full thrust is programmed at 0.4 seconds. A "Chi-freeze" program is available to simulate minimum load tilt maneuvers following an engine failure.

Some aspects that are not taken into consideration by the program are:

a. vehicle non-symmetry

b. unsteady aerodynamics (flutter)

c. cross-coupling of slosh-modes between the pitch and yaw planes.

Despite these items, it was indicated that realistic results which account for the effects of wind gusts and aerodynamic damping, with close to "real-life" (distributed) non-linear aerodynamic loads in three dimensions, are obtainable.

As a result of simulation runs with the program, it appears* that improved (single) engine-out capability could be attained by means of a modified Flight Control System (i.e., increased gain, different gain switching times, and different filter characteristics). If, in addition, the tension capability at certain critical stations is strengthened, then the basic problem is diminished. That is, in the event of an engine failure, vehicle breakup might occur only during a relatively brief period and under conditions of much higher wind velocities.**

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*Per telecon of March 23, 1967, with Mr. J. Gelzer of TBC.

**The values of the times and wind velocities were not available at the time of the telecon, but will be published shortly.

It was indicated that MSFC is working with the stage contractors to test the six critical joints and define the details of strengthening for those joints that cannot meet the new loads. MFSC-ASTR has also initiated the previously discussed changes in the Flight Control System. These changes were indicated to be effective for AS-502 and subs, with a possibility for even the AS-501 mission.

H E Stephens
for T. F. Loeffler

2031-TFL-sam

Attachments
References
Figures 1-5
Appendix A

Copy to
Messrs. L. E. Day - NASA/MAT
G. F. Esenwein, Jr. - NASA/MAT
J. K. Holcomb - NASA/MAO
T. A. Keegan - NASA/MA-2
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C. Bidgood
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J. J. O'Connor
T. L. Powers
I. M. Ross
W. Strack
T. H. Thompson
G. B. Troussoff
R. L. Wagner
Central Files
Department 1023
Department 2031
Library

REFERENCES

1. Purdy, M. M. Implications of Recent Flight Limits Analyses of Saturn V to Emergency Detection System Effectiveness, memorandum for file, dated November 10, 1966.

2. Purdy, M. M. EDS Effectiveness: Follow-Up on Saturn V Flight Limits Analyses, memorandum for file, dated December 7, 1966.

3. Loeffler, T. F. & Purdy, M. M. EDS Effectiveness: Status of Saturn V Launch Vehicle Analyses, memorandum for file dated January 12, 1967.

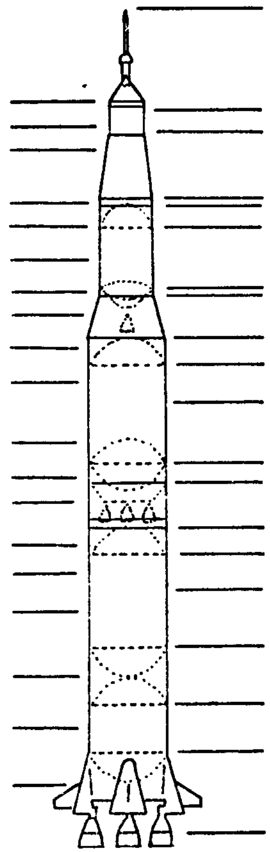
4. Stephens, H. E. Saturn V Engine-Out Structural Capability, memorandum for file, dated April 11, 1967.

5. Loeffler, T. F. Seventh Flight Limits Subpanel Meeting, February 14, 1967, memorandum for file, dated March 17, 1967.

② NINETEEN PANEL AERODYNAMICS REPRESENTATION

AERO REF STATIONS

R	X_R METERS	INCHES
19	97.240	3828.340
18	93.357	3675.484
17	87.031	3426.400
16	82.313	3240.676
15	79.799	3141.676
14	75.343	2966.248
13	70.847	2789.236
12	66.873	2632.816
11	62.307	2453.032
10	57.207	2252.260
9	50.358	1982.584
8	45.821	1803.988
7	41.919	1650.340
6	37.362	1470.952
5	32.484	1278.892
4	26.268	1034.164
3	19.227	756.964
2	12.276	483.328
1	3.656	143.956



PANEL BOUNDS

4240.792
3756.555
3594.555
3258.555
3222.555
3100.555
2832.0
2745.5
2519.0
2387.0
2117.5
1848.0
1760.0
1541.0
1401.0
1156.5
912.0
602.0
365.0
-115.494

FIGURE 1

③ TYPICAL 3-D TABLE

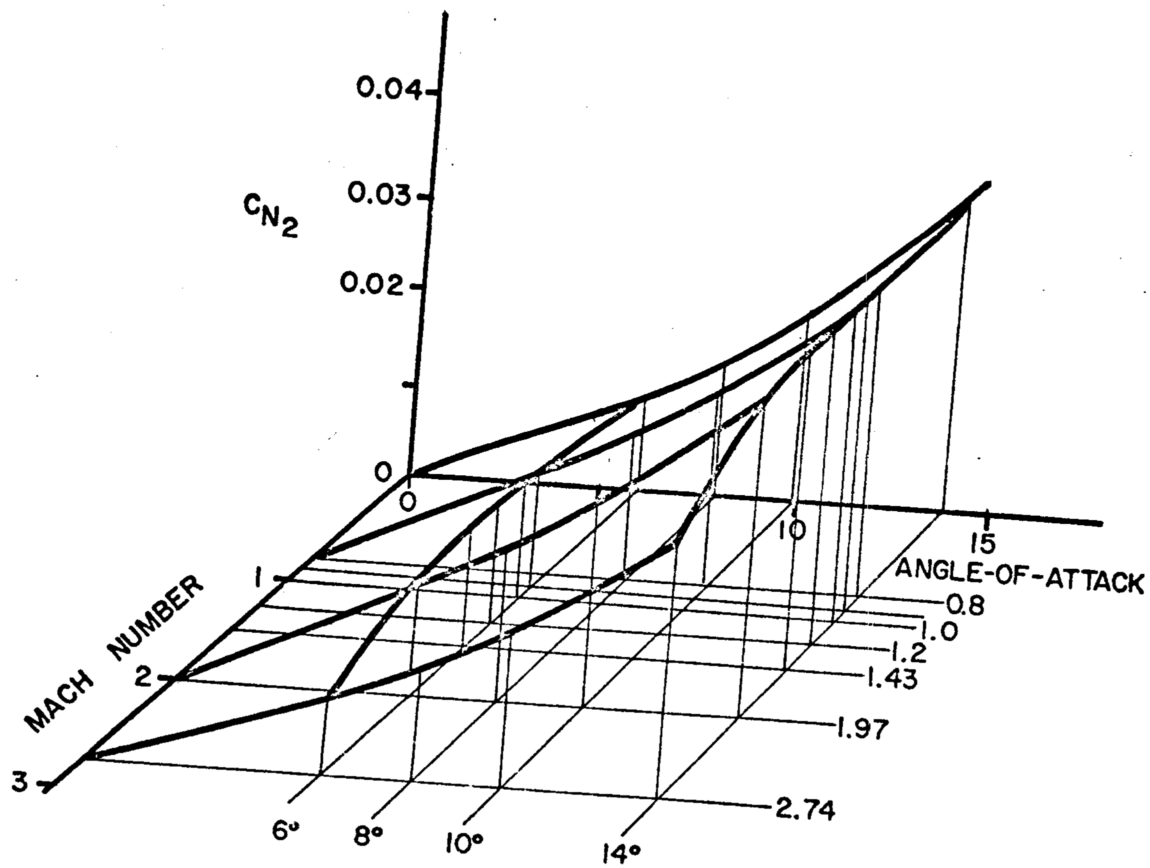
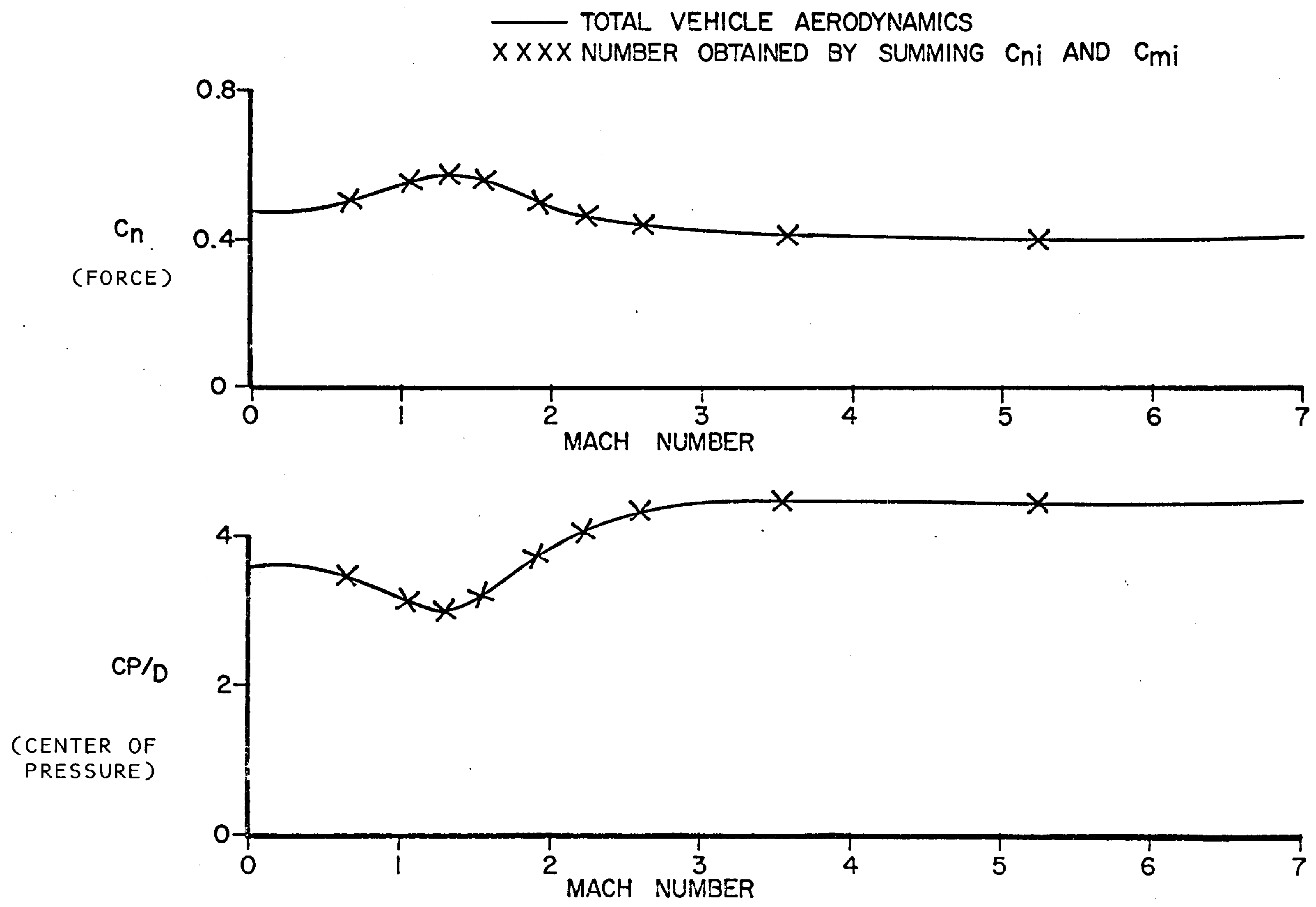


FIGURE 2

④ DISTRIBUTED AERO CHECK



○ THIS CHECK DONE BY AERO CHECK PROGRAM

FIGURE 3

APPENDIX A

MSFC-152 Study

The following are the highlights of the description of the MSFC-152 study. The 14 page handout is also attached.

I. SA-503 Analysis by May 1, 1967, modify same for SA-504 Analysis by June 1, 1967

II. BHA-0030 Digital Simulation obtains detailed flight dynamics and loads. BHA-0097 Hybrid Simulation used to obtain parametric data, and relative effect of vehicle changes being evaluated.

III. Malfunctions simulated:

A. Loss of thrust (single engine)

B. Single actuator hardover

C. Single actuator at null

D. Loss of guidance command

E. Loss of inertial attitude

F. Saturated control signal

IV. Baseline for study: SA-503 vehicle (as defined)

V. Vehicle changes considered and evaluated as follows:

A. Control

1. Increase Flight Control System (attitude) gain and modification of (attitude) filter characteristics

2. Addition of accelerometer (feedback) control and load relief

3. Removal of fins

4. Gimbal control response to balance asymmetric thrust condition

5. Shutdown of opposite engine

B. Guidance

1. Wind biasing of trajectory for load reduction

2. Delay of "chi-freeze" program (after high-Q) engine out

3. Optimization of "chi-freeze" program for minimum vehicle loading

C. EDS Sensor(s)

1. Addition of "actuator at stops" signal from gimbal position to drive engine-out light(s) in CM

2. Utilization of accelerometer to indicate excessive lateral forces

3. Derive platform malfunction indications from the "Guidance Failure" light in the CM

4. Obtain secondary cues for manual abort from the rate gyro and Q-ball signals

5. Use the "engine-out" signal to initiate control responses described in A-4 and A-5 above

D. Vehicle Structural

1. Strengthen critically loaded L/V joints

2. Improve marginal S/C structural members

E. Abort System

1. Improve Launch Escape System (LES) abort capability, to enable abort with a wider range of angle of attack limits

VI. The evaluation includes:

A. Malfunction description, including thrust decay (for engine-out) actuator rate (for hardover), "guidance reasonable" test (for platform failures).

B. Test dynamics and EDS sensor performance histories after malfunction

C. Bending moment, axial load, total load(s) and load indicator calculations for critical stations of the L/V and the S/C.

VII. The desired results are:

A. Structural capability assessment for possible breakup conditions and locations of improved capability to assure safe abort

B. Evaluation of improvements of Crew Safety available by combining of the various vehicle changes to baseline vehicle. Criteria for this evaluation are:

1. Structural integrity

2. Vehicle controllability

3. LEV initial condition abort limits

Evaluation is to include:

1. Effects of wind magnitude

2. Effects of wind direction

3. Effects of gust phasing

4. Effects of vehicle tolerances

5. Effects of time of malfunction

VIII. Final Documentation will include:

A. Definition of predicted vehicle load responses for specific flight conditions and malfunctions

B. Final structural loads for the specific flight conditions, and comparisons of these loads to 503 and 504 vehicle capability

C. Recommendations for required S/C and L/V capabilities to ensure safe abort.

STATUS REPORT

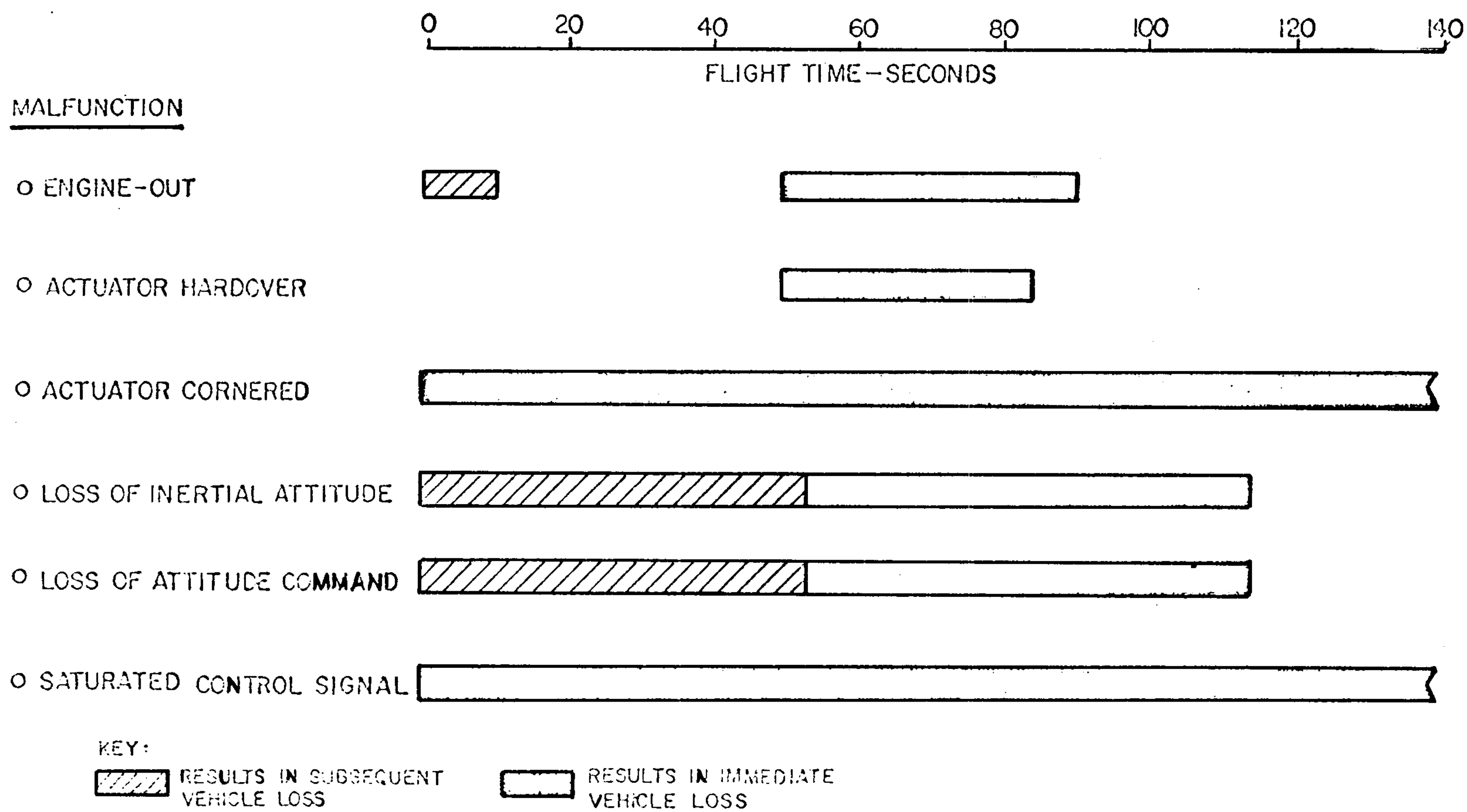
SATURN V EDS LIMITS PROBLEM

MALFUNCTIONS WITH SIGNIFICANTLY HIGH PROBABILITY OF OCCURRENCE MAY RESULT IN VEHICLE LOSS

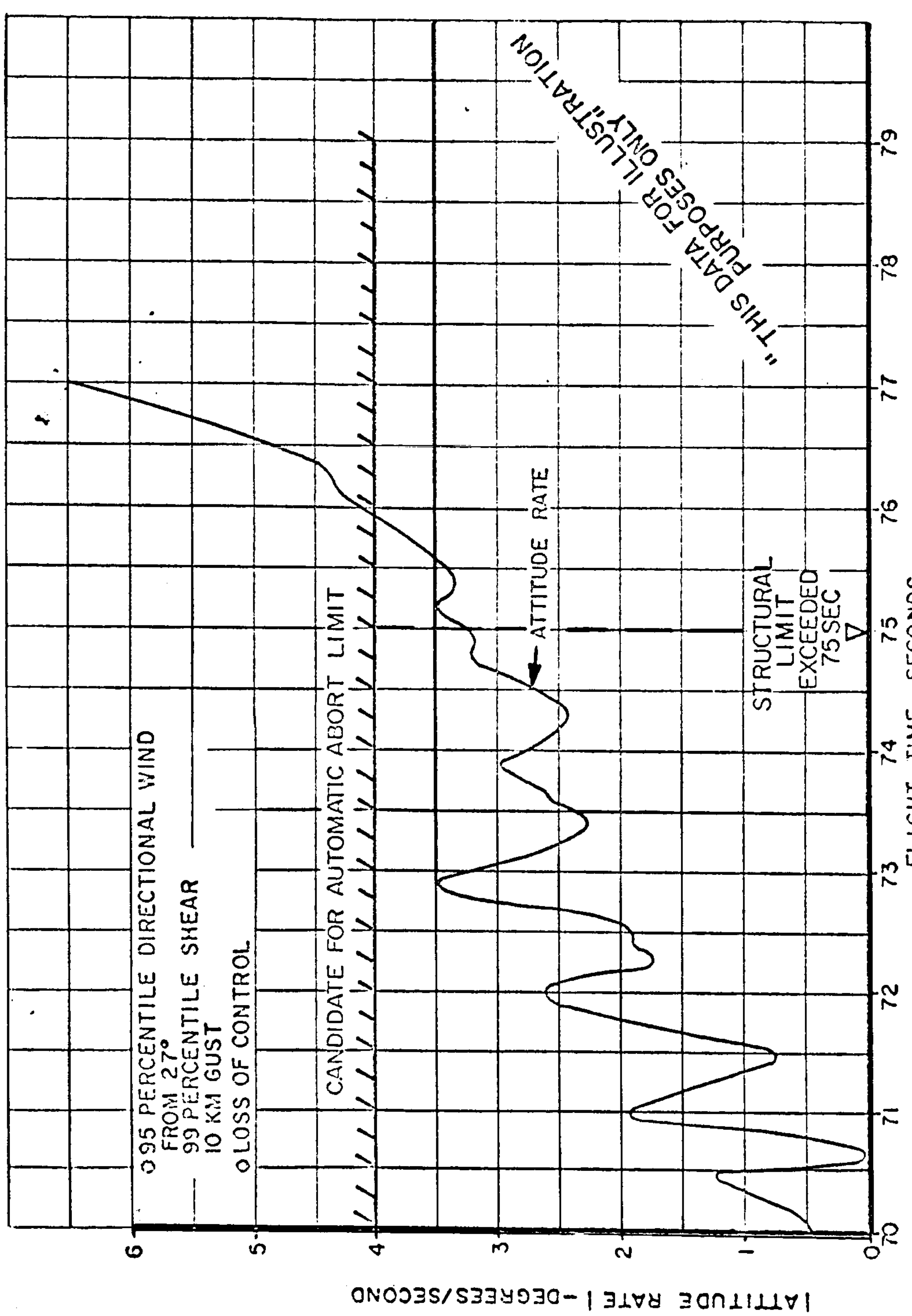
- DURING S-IC BURN
- WITH WINDS LESS THAN 95 PERCENTILE

EDS MAY NOT PROVIDE CREW SAFETY FOR THESE VEHICLE LOSS CASES. THIS IS SHOWN IN D5-15555-2, DATED NOVEMBER 21, 1966.

FLIGHT REGIONS OF POSSIBLE VEHICLE LOSS



—EXAMPLE—
EDS LIMIT SETTING FOR AUTOMATIC ABORT
3 ENGINE-OUT AT 70 SECONDS



ACTION TAKEN

CHANGE ORDER MSFC-152 AUTHORIZED BOEING FEBRUARY 1, 1967, TO DEFINE REQUIREMENTS FOR THE LAUNCH VEHICLE AND SPACECRAFT TO ATTAIN AN ACCEPTABLE EMERGENCY DETECTION SYSTEM EFFECTIVENESS DURING S-IC BURN FOR VEHICLES 503 AND 504.

UNDER MSFC-152, A JOINT STUDY EFFORT IS IN PROGRESS WITH STRUCTURES, GUIDANCE, AND CONTROL ELEMENTS OF MSFC AND BOEING. THIS WILL RESULT IN DEFINING THE RISK TO CREW SAFETY FOR VARIOUS COMBINATIONS OF FEASIBLE DESIGN CHANGES. NASA WILL ADD SCHEDULE AND COST IMPACT TO DECIDE UPON IMPLEMENTATION OF CHANGES.

OBJECTIVES OF MSFC-152

PROVIDE EVALUATION LEADING TO PREVENTION OF SUDDEN VEHICLE BREAKUP AFTER ENGINE-OUT.

PROVIDE EVALUATION TO ALLOW DECISION ON NEED FOR STRUCTURES, GUIDANCE, CONTROL, AND EDS CHANGES. EVALUATION SHALL SHOW RISK TO CREW SAFETY FOR TYPE OF MALFUNCTION, VARYING WINDS, VEHICLE TOLERANCES, AND TIMES OF MALFUNCTION.

APPROACH FOR MEETING MSFC-152 OBJECTIVES

SUDDEN BREAKUP AFTER ENGINE-OUT:

DETAILED LOADS CALCULATION AFTER MALFUNCTION BEING PERFORMED FOR BOTH LAUNCH VEHICLE AND SPACECRAFT STATIONS. (R-P&VE/BOEING STRUCTURES/MSC)

STRUCTURAL CAPABILITY OF LAUNCH VEHICLE BEING ANALYZED FOR MARGINAL OR BREAKUP CASES. (R-P&VE/BOEING STRUCTURES)

SPACECRAFT CAPABILITY PROVIDED BY MSC BEING COMPARED AGAINST EXPECTED LOADS. REPRESENTATIVE DATA INDICATING POSSIBLE (F.S. <1.1) SPACECRAFT BREAKUP WILL BE FORWARDED TO MSC FOR FURTHER ANALYSIS.

NEED FOR MODIFYING CRITICALLY LOADED JOINTS OF VEHICLE STRUCTURES BEING EVALUATED. (MSFC)

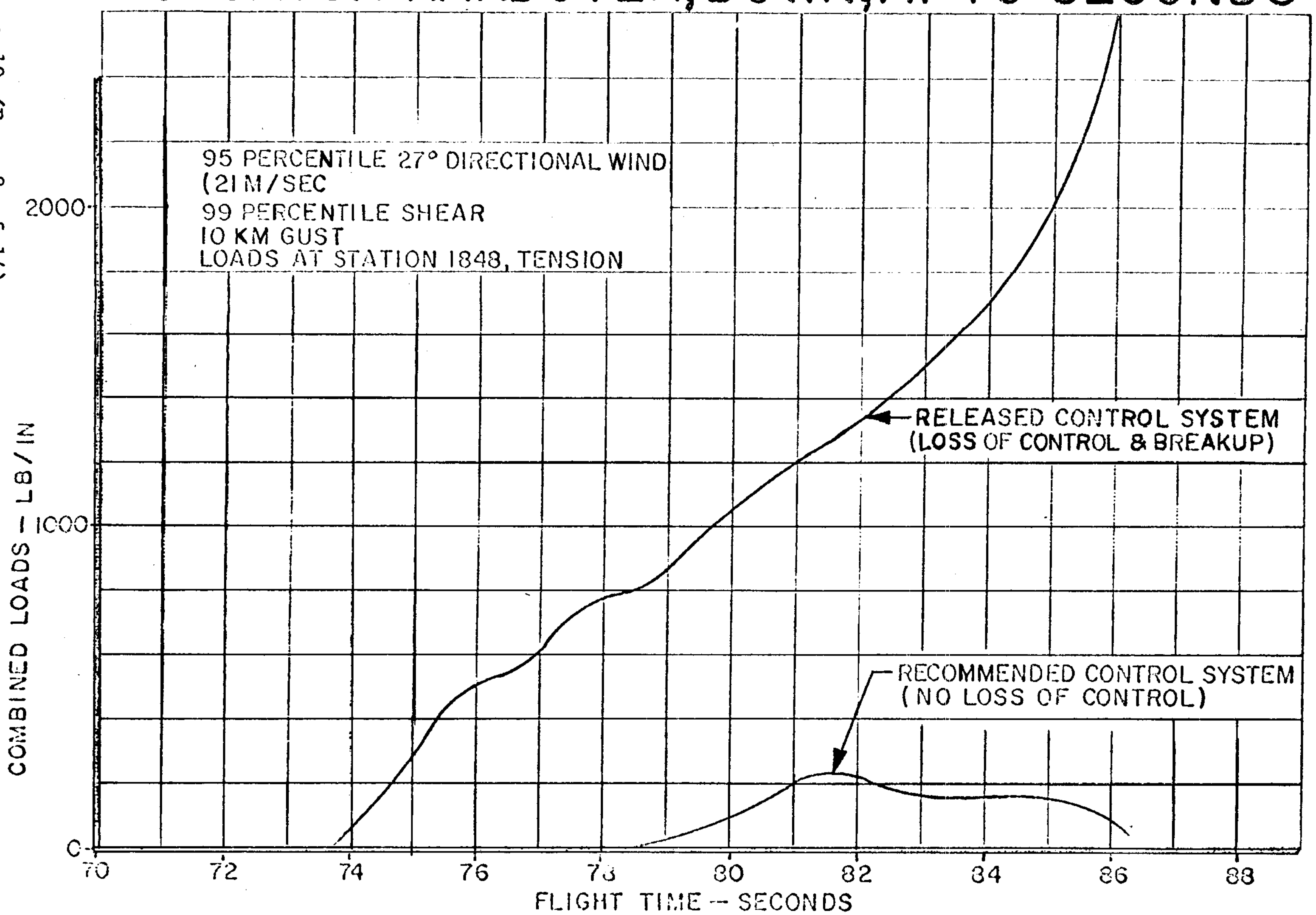
APPROACH FOR MEETING MSFC-152 OBJECTIVES

FOR MALFUNCTIONS RESULTING IN LOSS-OF-CONTROL THE FOLLOWING CHANGES ARE BEING EVALUATED:

- CONTROL SYSTEM
  - GAIN CHANGES
  - ACCELERATION FEEDBACK
  - REMOVAL OF FINS (SSR)
- GUIDANCE PROGRAM
  - DELAY CHI-FREEZE
  - OPTIMIZE CHI-FREEZE
- EDS SENSORS AND LOGIC
  - GIMBAL ANGLES
  - ENGINE-OUT LIGHTS
  - GUIDANCE FAILURE LIGHT
  - MANUAL ABORT PROCEDURES
- LAUNCH VEHICLE STRUCTURES
  - INCREASE CAPABILITY
- SPACECRAFT
  - INCREASE LEV-ALPHA LIMITS
  - INCREASE STRUCTURAL CAPABILITY

—EXAMPLE—

STRUCTURAL CAPABILITIES - # 3 ENGINE PITCH ACTUATOR HARDOVER, DOWN, AT 70 SECONDS



NEW EDS SENSORS - EXAMPLE

- SUPPLEMENT GROSS, VEHICLE MALFUNCTION INDICATORS, I.E.,

    VEHICLE OVERRATE

    Q-BALL PRESSURE

    TWO ENGINES-OUT

  WITH SUBSYSTEM MALFUNCTION INDICATORS

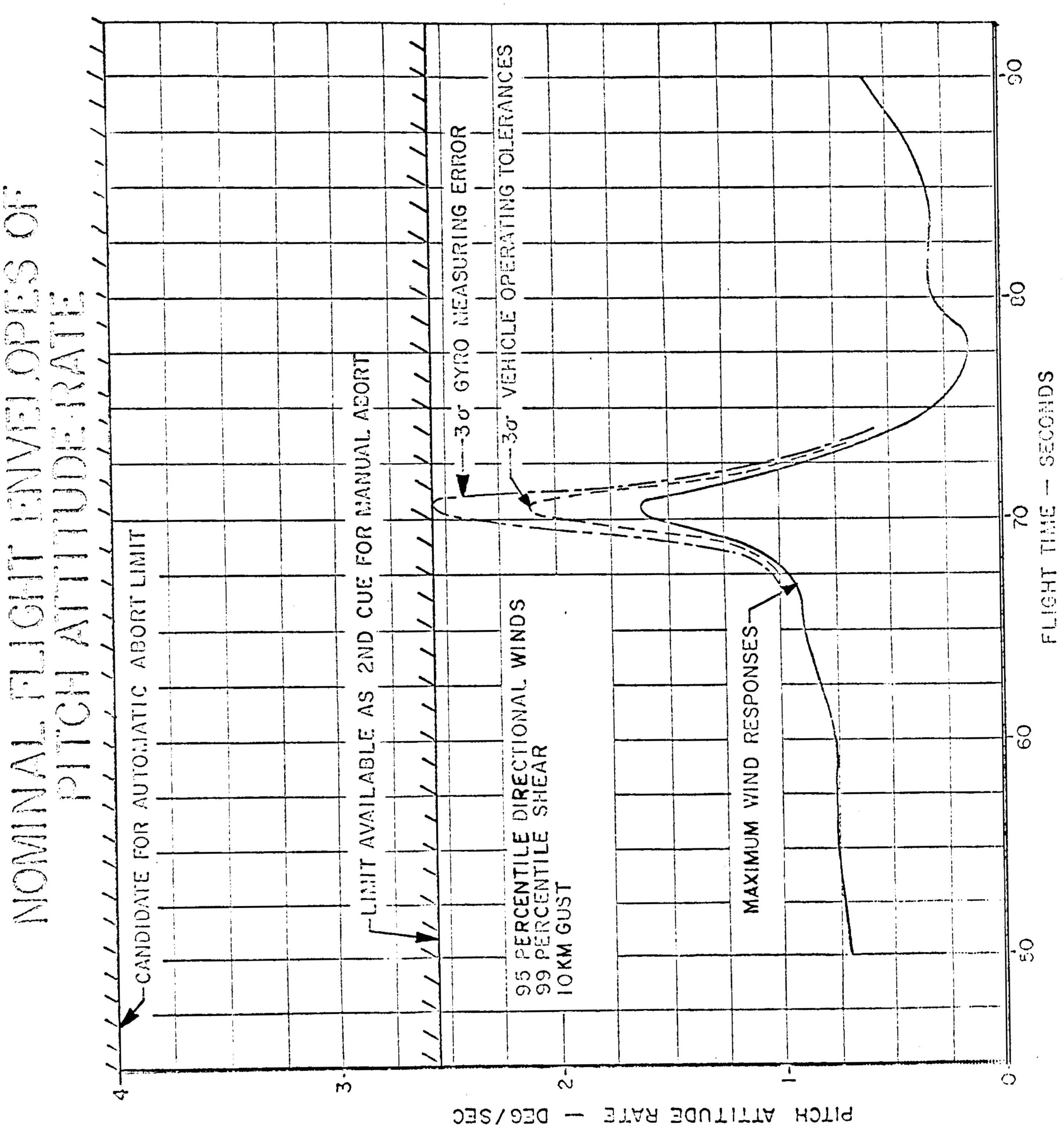
    ENGINE-OUT LIGHT

    GUIDANCE FAILURE LIGHT

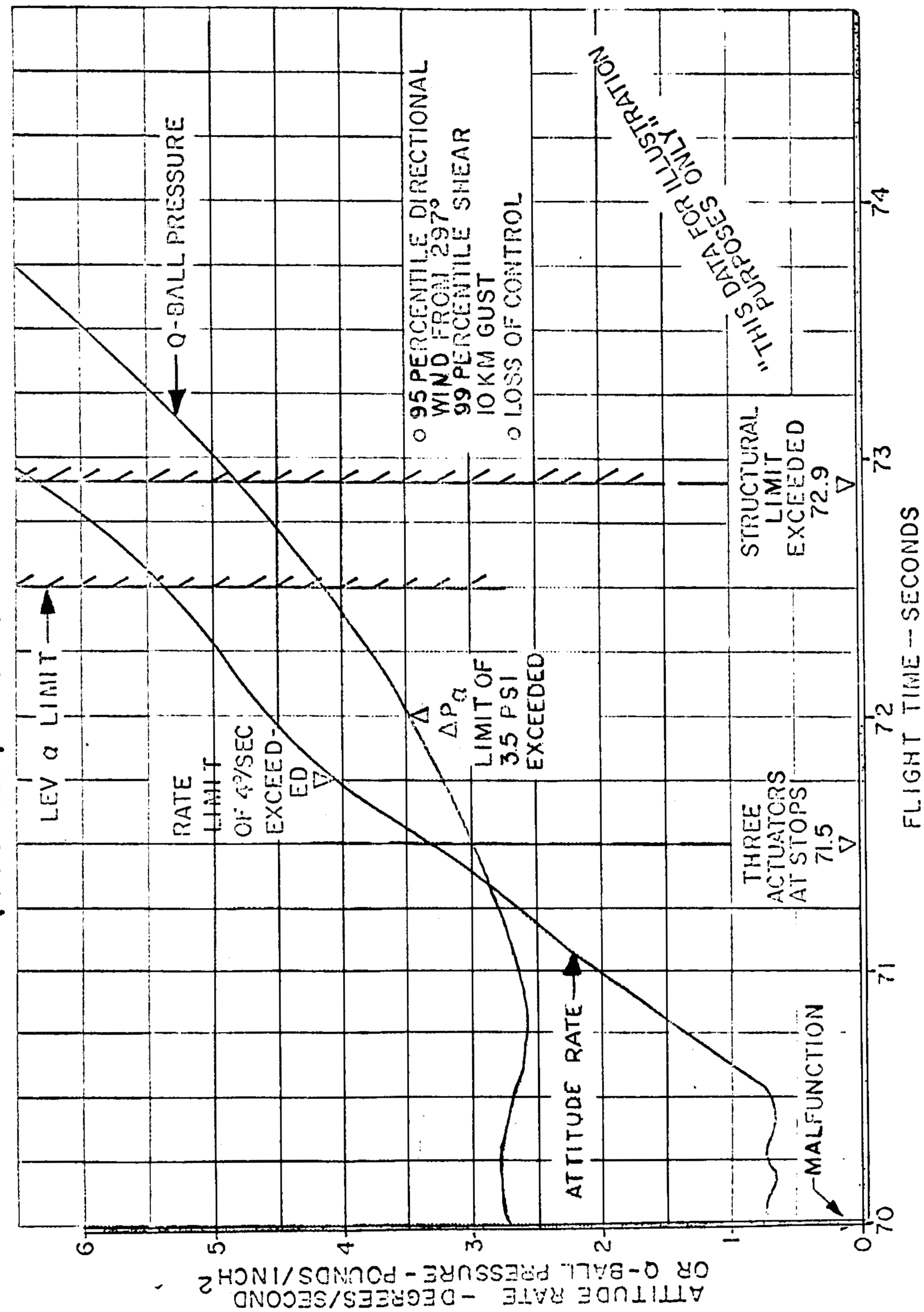
    ACTUATOR AT STOPS LIGHT

  AND PHYSIOLOGICAL INDICATORS

- TO ACHIEVE EARLIER WARNING AND PROVIDE TWO CUES FOR MANUAL ABORT


NOMINAL FLIGHT ENVELOPES OF
PITCH ATTITUDE RATE
CANDIDATE FOR AUTOMATIC ABORT LIMIT
LIMIT AVAILABLE AS 2ND CUE FOR MANUAL ABORT
3σ GYRO MEASURING ERROR
3σ VEHICLE OPERATING TOLERANCES
95 PERCENTILE DIRECTIONAL WINDS
99 PERCENTILE SHEAR
10KM GUST
MAXIMUM WIND RESPONSES
PITCH ATTITUDE RATE — DEG/SEC
4
3
2
1
0
FLIGHT TIME — SECONDS
50
60
70
80
90

EDS PARAMETERS #1 ENGINE CORNERED (ROLL) AT 70 SECONDS

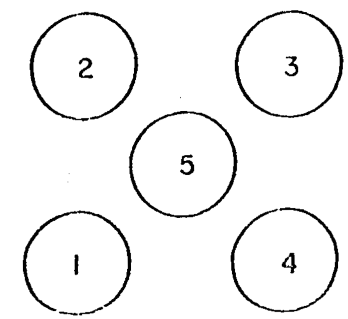


POSSIBLE ABORT LOGIC TO PROVIDE EARLY WARNING

FOR ENGINE-OUT OR ACTUATOR MALFUNCTIONS, LOSS-OF-CONTROL CASES

$i^{\underline{th}}$ SINGLE ENGINE-OUT SIGNAL FROM ENGINE-OUT CIRCUITRY ⟶ $i^{\underline{th}}$ LIGHT ON

$j^{\underline{th}}$ SINGLE ACTUATOR TO STOPS (EITHER PITCH OR YAW, INCLUDING MALFUNCTIONED ACTUATOR; OTHER ACTUATORS TO STOPS AS A RESULT OF CONTROL RESPONSE) ⟶ $j^{\underline{th}}$ LIGHT ON



---DISPLAY---
ENGINE-OUT LIGHTS

MANUAL ABORT LOGIC:

$$\left\{ \begin{matrix} \text{ANY TWO OR MORE LIGHTS} \\ + \\ \text{FLIGHT DYNAMIC CUES} \end{matrix} \right\} \longrightarrow \text{ABORT}$$

APPROACH FOR MEETING MSFC-152 OBJECTIVES

THE EVALUATION WILL:

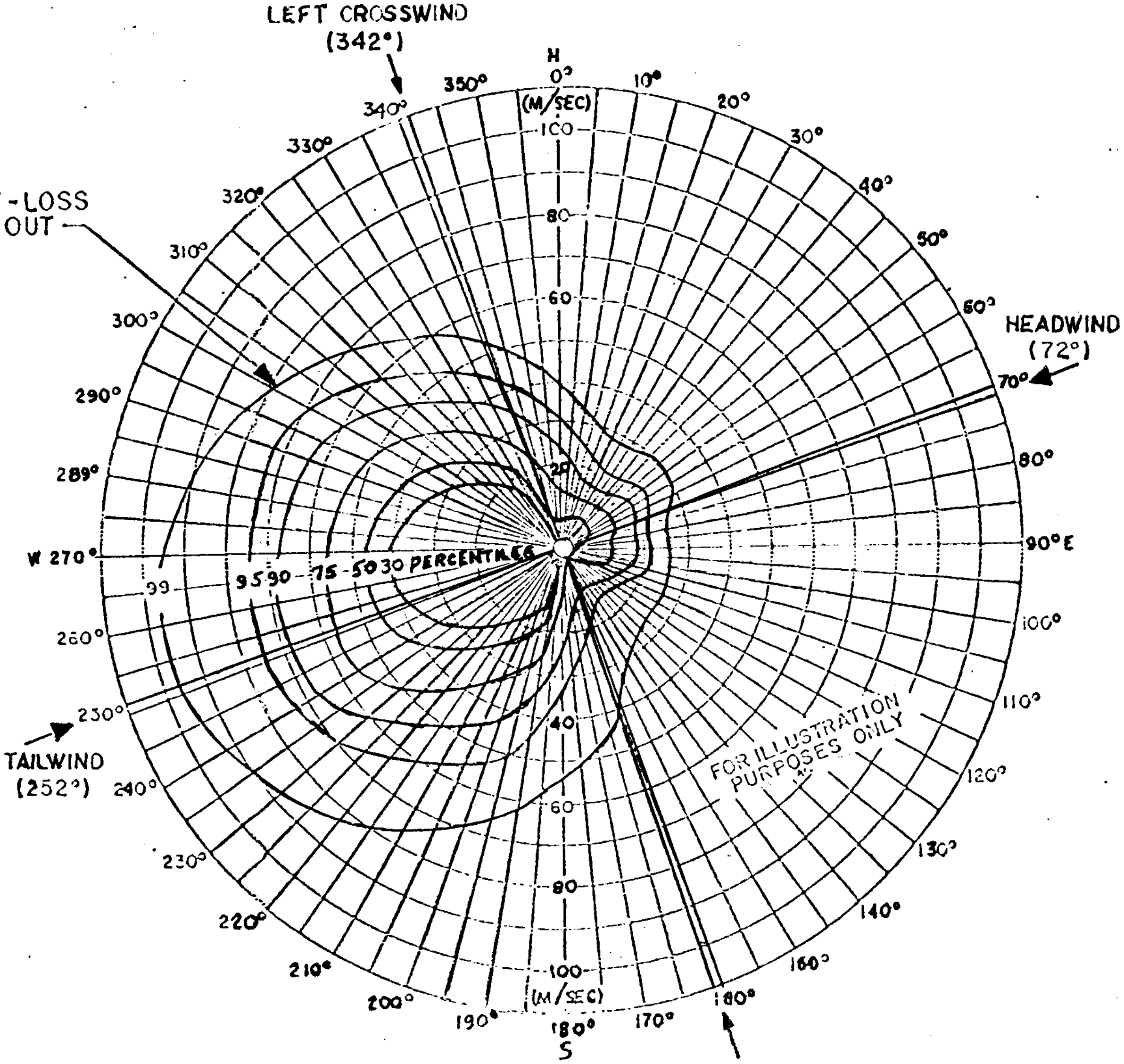
FOR EACH MALFUNCTION AND BASELINE VEHICLE AND SYSTEM CONFIGURATION, SHOW REGIONS OF:

- WIND MAGNITUDE
- WIND DIRECTION
- FLIGHT TIME

FOR WHICH CREW SAFETY IS NOT ASSURED

SHOW HOW THESE REGIONS ARE REDUCED BY VARIOUS COMBINATIONS OF CHANGES TO THE BASELINE.

RISK EVALUATION FOR DIRECTIONAL WIND ENVELOPES



BASED ON SIX YEARS RAWINSONDE SERIALLY COMPLETE DATA RECORD AT CAPE KENNEDY, FLA
REF: R-AERO-YT, DECEMBER 5, 1963